HOUSTON, TEXAS

STRUCTURE 59. This single-family home was constructed in 1983 on 10-inch by 10-inch wooden posts spaced about 10 feet apart. The posts varied in embedment depth below grade from 4 feet to 8 feet with no concrete in the post hole. The building's first floor was elevated about 10 feet above grade. The building was located about 30 feet from the bank of the San Jacinto River. The flood depth was about 4 feet around the structure. A concrete slab-on-grade was in place beneath the structure. A closed-in utility room was in place in the lower area between the slab-on-grade and the first floor of the structure. This enclosure was located near the "upstream" corner of the structure. Failure occurred at the upstream end of the structure due to scour to depths below post embedment.

Lesson. This structure was exposed to extreme high velocities. Structure failure occurred because of four basic reasons. First, the enclosed lower area utility room created even higher localized velocities than already present as the floodwater flowed around the obstruction. Second, the enclosed area was near the "upstream" corner of the structure so the localized velocity increase occurred near the slab edge where scour could occur beneath the slab. Third, perimeter footings were not in place under the slab-on-grade to prevent scour beneath the slab. Fourth, the post embedment depth was not deeper than the scour depth. These factors combined to create a situation conducive to massive scour and failure. The eastern portion of the structure, which did not have an enclosed area, functioned successfully.

Looking at the collapsed portion of the structure. The collapsed portion is at the left.
The river is behind the structure

STRUCTURE 60. This structure was a single-family home with its first floor elevated about 8 feet above a concrete slab-on-grade. This home sat directly east of Structure 59 and about 30 feet from the San Jacinto River. It was elevated on 10-inch by 10-inch wooden posts spaced from 12 to 16 feet apart. The entire area beneath the first floor was open for unobstructed floodflow. This home was not damaged to any great extent. The only visual damage was a small amount of scour along the north edge of the slab.

Lesson. This flood proofing system functioned very well. This appears to be due to the lack of a localized velocity-increasing mechanism, such as a lower enclosed area, that would create a situation conducive to large amounts of scour. This structure should be retrofitted with perimeter footings around the slab-on-grade embedded to below scour depth to prevent the amount of scour that did occur.

Looking away from the river at the structure. Note the area beneath the structure is completely open.

STRUCTURE 61. This single-family home was elevated on 8-inch by 8-inch wooden posts spaced about 10 to 13 feet apart. The posts were embedded about 3 to 4 feet below grade. The entire lower area was enclosed and used as living space. The structure was about 150 feet from the San Jacinto River. The floodwater depth in the area was about 6 feet. The first floor was elevated about 8 feet above grade. A concrete slab-on-grade was in place. Concrete was not placed around the base of the wooden posts. Failure occurred due to scour to depths greater than the bottom of the posts. Friction post support was removed due to the scour.

Lesson. Failure of the system occurred due to high localized velocities. Even though the structure was 150 feet from the riverbank, the localized velocities created by the water flowing around the enclosed lower area created conditions enabling localized scour to occur to depths that caused failure. The main deficiencies with this system are the enclosed lower area, which created high localized velocities; the lack of adequate post embedment depth; and the lack of perimeter footings beneath the slab-on-grade to prevent scour under the slab.

STRUCTURE 62. This single-family home was elevated on 8-inch by 8-inch wooden posts about 10 to 13 feet apart. The first floor was about 9 feet above the concrete slab-on-grade. The home was about 40 feet from the San Jacinto River. No damage occurred to the structure. No evidence of any scour was present.

Lesson. This flood proofing system worked well. No scour was evident, probably because of the "shield" effect of a row of trees and brush to the left (upstream) side of the structure. These trees apparently provided protection from the high velocities so scour did not attack even the slab-on-grade. The lack of an enclosed obstruction in the lower area prevented the creation of high localized scour-producing velocities. Scour was evident to the left of the row of trees.

Looking toward the river at the structure. Note the trees on the left that apparently protect this structure. Note, also the lack of any obstruction beneath the structure.

STRUCTURE 63. This single-family home was elevated about 8 feet from grade to the first floor. A concrete slab-on-grade was present. A closed-in lower area utility room was also present. The structure was about 150 feet from the San Jacinto River. Trees and brush were located between the river and the structure. No major scour was evident.

Lesson. This flood proofing system worked well, with no apparent damage. This structure was located just west of Structure 61, which failed. Two basic reasons exist for why this system worked and that for Structure 61 did not. First, the trees and brush provided velocity "protection" to Structure 63. Second, the enclosed area was set back about 10 feet from the edge of the concrete slab-on-grade so any localized high velocities caused by the enclosed obstruction acted upon the slab-on-grade and not on the scourable soil at the edge of the slab.

STRUCTURE 64. This single-family home was elevated 13 feet 5 inches above grade on columns made of 12-inch by 16-inch concrete block. The columns were grouted with concrete and contained six rebars each running the full column length and tying into the foundation. The foundation was a "floating concrete slab" comprised of 18-inch-deep by 12-inch-wide reinforced concrete beams buried just below grade horizontally with a 6-inch concrete slab on top of the beams at grade. The columns were about 11 to 12 feet apart. The structure was about 150 feet from the San Jacinto River. Debris accumulated at the northeast corner of the structure. This debris obstruction, coupled with high-velocity floodwater, caused hydrodynamic force to slightly tip this floating structure. Considerable scour occurred around the debris accumulation.

Lesson. This structure received relatively little flood-related damage during this event. The home was realigned and the scoured area filled. Even with this "success," this flood proofing system should not be promoted. The risk to this structure is great for two reasons--both related to debris accumulation. First, severe debris accumulation, coupled with hydrodynamic force, could tip over the structure. Second, scour could severely undermine this structure's foundation because of debris accumulation, also resulting in the structure tipping.

Looking NW at the structure. The San Jacinto River is at far right outside of the photograph.

STRUCTURE 65. This single-family home was elevated on wooden posts. It was located a considerable distance from the San Jacinto River. Damage occurred to this structure because of localized scour and shallow post embedment depth coupled with concrete placement around the post only at the surface. A portion of the lower area was enclosed, creating a condition for high localized velocities and scour.

Lesson. Damage occurred with this system because of the enclosed lower area, which created high localized velocities and scour, and the extremely shallow post embedment depth. If the posts had been embedded to a greater depth and placed in concrete and the enclosed area had not been present, this structure would probably have sustained no damage.

Looking at the structure.

Looking at the structure's shallow post embedment depth.

STRUCTURE 66. This single-family house was elevated about $9^{1}/_{2}$ feet from first floor to concrete slab-on-grade by 10-inch by 10-inch wooden posts located from 10 to 12 feet apart. The posts were embedded from 6 feet to 10 feet below grade without concrete. Floodwater depth was about 6 feet. An enclosed utility area was located in the central portion of the lower area. The structure was located about 40 feet from the San Jacinto River. Failure occurred due to scour.

Lesson. This structure had an enclosed area in the central portion of the lower area between the slab-on-grade and the first floor of the home. This enclosed area was conducive to creating high localized velocities. Its location, however, in the central part of the lower area surrounded by a concrete slab for some distance proved in other structures to be not nearly as damaging due to scour as when located near the upstream edge of the slab. Apparently, the tremendous scour that occurred at this structure was aggravated by the enclosed area but was created mostly by the structure's location along the river. Perimeter footings under the slab-on-grade would have greatly reduced the scour even in this apparently bad location. Post embedment depth obviously should have been deeper. For definite protection from this type of damage, piles driven to below the scour depth would have been the ultimate solution.

Looking at tilted structure as a result of scour under the left portion of the structure.

<u>STRUCTURE 67</u>. This single-family home was located about 100 feet from the San Jacinto River. The home was slab-on-grade construction, with the first floor elevated on extended foundation walls and the lower area completely enclosed except for doors and windows. No evidence of any scour was present. One side of the home collapsed, probably because of hydrodynamic force against the extended foundation wall. No reinforcement or grouting was evident in the foundation wall. Flood depth in the area was about 11 feet above grade.

<u>Lesson</u>. This flood proofing system failed for basically two reasons. First, the lower area was completely finished, creating high localized velocities that resulted in extensive damage to the interior. Second, extended foundation walls were used, inappropriately, in high-velocity areas, subjecting the structure to hydrodynamic force.

Looking at the failed structure.

<u>STRUCTURES 68, 69, 70, 71</u>. These structures were all single-family homes. Severe erosion occurred because of deep floodflows at high velocity as floodwater from the San Jacinto River exited the channel to flow overland across a peninsula created by large bends in the river channel. As seen in the photograph, the homes were totally destroyed.

<u>Lesson</u>. No flood proofing system can withstand erosion such as that experienced here. Construction of any type in an area where extremely high velocities can occur is not advised and reflects extremely poor judgment.

Looking across the area previously occupied by these structures.

FLORIDA PANHANDLE

During the fall of 1995, hurricanes struck the Florida panhandle with hurricane force winds, wave runup, heavy rainfall, and flooding. Development along the shoreline sustained damage from flooding, wind, erosion, and hydrodynamic force.

PANAMA CITY, FLORIDA

STRUCTURES 72, 73. These structures were located directly on the beach. They were elevated on extended foundation walls made of concrete block with slab-on-grade construction and shallow footings. The lower (at grade) floor was finished with large glass windows facing the ocean. A concrete slab seawall was located between the structures and the ocean. Floodwater damaged the lower at-grade first-floor level. Hydrodynamic force broke the windows. Scour under the slab-on-grade foundation did not occur because of the presence of the seawall.

Lesson. Slab-on-grade construction with shallow footings should not have been used in this location because of the enormous potential for scour. The lower floor should not have been developed because of the great potential for flooding from hurricane force wave runup. These structures, as built, were saved from major structural damage by basically two items. One, the presence of the large plate glass windows on the lower floor broke under wave force, allowing flood damage to occur but reducing the potential for complete wall failure due to hydrodynamic force. Two, the presence of the seawall protected the slab-on-grade foundation from extensive scour, which would have allowed substantial structural failure to occur.

Looking at the slab-on-ground structures and the seawall.

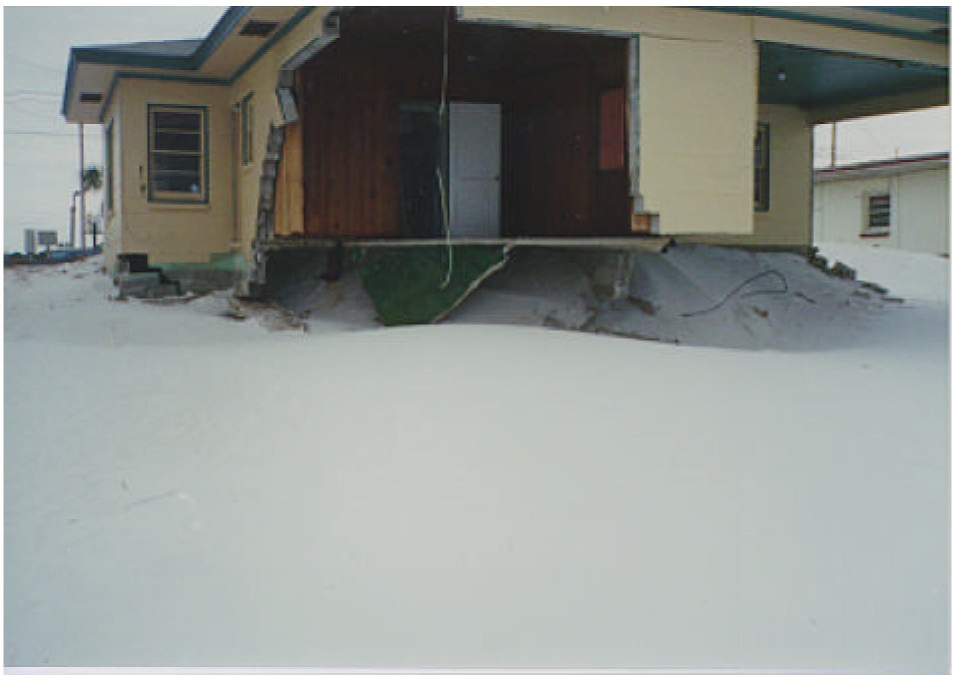
STRUCTURE 74. This structure was elevated on extended foundation walls on shallow footings with the first floor consisting of concrete on sandfill placed within the perimeter formed by the extended foundation walls. The structure was located directly on the beach. Scour undermined the shallow footings along one side of the structure, causing collapse of the extended foundation wall, erosion of the sandfill placed within the perimeter formed by the extended foundation walls, collapse of the concrete floor, and subsequent failure of the concrete block wall and also the roof. Floodwater inundated the first floor.

Lesson. Four basic problems were present with this structure. First, the footings were too shallow, allowing scour to undermine them. Second, extended foundation walls, which are not appropriate for coastal areas subject to hydrodynamic force, were used. In this particular case, failure did not occur because of extended walls, but they made the structure highly susceptible. Third, the concrete slab for the first floor was supported by sandfill. When the perimeter wall failed, erosion of the sandfill occurred, causing the floor to collapse. The floor should have been supported on piles driven to a depth below the potential scour, or the perimeter footings supporting the extended foundation walls should have been constructed to below-scour depth. Fourth, the structure was not elevated enough to prevent floodwater damage. Structures such as this in this location need to be elevated on piles.

Looking at the structure with the beach in the background.

STRUCTURE 75. This structure was very similar in construction to Structure 74, and similar failure occurred. The structure directly fronted the beach, had extended foundation walls on shallow footings with some elevation, and had a first floor slab on sandfill retained by the perimeter extended foundation walls. In the case of Structure 75, the failed wall directly faced the beach; the failed wall on Structure 74 did not. Location of the failed wall may have caused failure of the structure due to both scour under the footings and hydrodynamic force against the extended foundation walls. Erosion of the sandfill allowed failure of the concrete floor slab. Floodwater inundated the first floor.

Lesson. This structure had the same basic four problems as Structure 74--shallow footings, extended foundation walls, concrete slab on sandfill, and inadequate structure elevation. Extended foundation wall failure was due first to scour and then to hydrodynamic force. The roofline on this structure was maintained, unlike that on Structure 74, probably because of the presence (in the middle of the structure) of the concrete block support for the floor and interior wall. This example shows the importance of multiple supports beneath a structure in an area subject to excessive scour. As stated for Structure 74, a structure with extended foundation walls, shallow footings, and a concrete slab on sandfill is definitely not appropriate at this location.



Looking from the beach at the structure.

STRUCTURE 76. This structure was located adjacent to Structure 75, so it was subjected to similar forces. Structure 76 differed from Structure 75 in its support system. Structure 76 was supported on wood piles embedded to below the scour depth that occurred in the Fall of 1995. Structural failure of this structure did not occur, although the structure was inundated by floodwater.

Lesson. This structure performed well except for one problem--it was elevated to an insufficient height to prevent damage from floodwater. The structure support system of wood piles functioned well. The concrete first floor slab remained intact because of the adequate wood pile support even though the sand had been removed from beneath the slab.

STRUCTURES 77, 78 . These structures directly faced the beach. Structure 77 was a one-story residential structure constructed on extended foundation walls. Failure of the footings and extended foundation walls occurred because of the combination of scour and hydrodynamic force. This was followed by first-floor concrete slab failure, wall failure, and roofline failure. Floodwater inundated the first floor. Structure 78 was a two-story residential structure constructed at basically the same first-floor elevation as Structure 77. Structure 78 was supported on wood piles embedded below the scour depth. No structural failure occurred. The first floor was flooded.

Lesson. Comparing Structures 77 and 78, located adjacent to one another, shows the inherent problem with shallow footings, extended foundation walls, and a first- floor concrete slab supported by sandfill. Scour undermined the shallow footings of Structure 77, causing, with hydrodynamic force, the failure of the extended wall foundations. This allowed erosion of the sandfill supporting the first-floor concrete slab and failure. In contrast, Structure 78, supported on piles embedded below scour depth, sustained no structural damage. Both structures were flooded because of inadequate elevation.

Looking at the structure with extended foundation walls on the left
and at the structure with a pile support foundation on the right.

STRUCTURE 79. This structure was a two-story residential structure facing directly toward the beach. It was elevated higher than many along the beachfront. It was supported by extended foundation walls on shallow footings with a concrete slab placed on sandfill for support. Failure occurred because of failure of the footings, walls, and slab. Failure due to tremendous wind damage and hydrodynamic force was also apparent. This structure was totally destroyed.

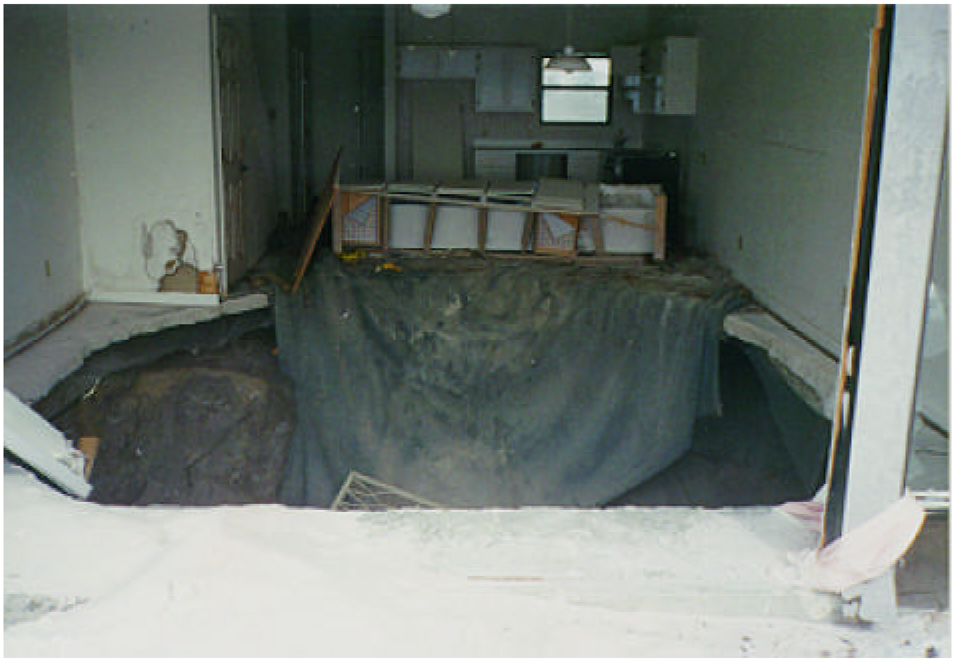
Lesson. This structure is discussed because it sustained massive damage even though it was elevated as much or more than most structures along this reach of beachfront. Failure probably started to occur because of scour beneath the shallow footings and hydrodynamic force against the extended foundation walls and the structure itself. Erosion of the sandfill caused concrete slab failure. Failure of these foundation elements substantially weakened the structural integrity of the wood-frame structure, allowing wind and hydrodynamic force to cause a near total destruction. A foundation of piles embedded below scour depth, with the piles extending to the roofline for proper structure/footing tie-in, and hurricane fasteners would probably have allowed this structure to sustain minimal damage.

Looking at the totally failed structure from the beach.

<u>STRUCTURE 80</u>. This structure was a two-story reinforced concrete multifamily dwelling. It was slightly elevated on wood piles. The piles were located beneath the bearing walls of the structure but not under the concrete slab on the first floor. The slab was supported by sand fill. Damage occurred due to erosion of the sandfill beneath the concrete slab, which allowed the concrete slab to drop. The structure was not elevated enough to prevent flood damage. Other than the floor damage, no basic structural damage occurred.

<u>Lesson</u>. The structure performed adequately except for two reasons. One, the structure was not elevated high enough to prevent flooding. Two, the concrete slab on the first floor was supported only by sandfill. When the sand eroded, the floor collapsed. Floor collapse could have been prevented by placing supporting posts beneath the concrete slab or by using rebar to support the floor from the piles located beneath the bearing walls.

Looking at the structure. Note that the building structure did not collapse due to the pile support foundation.



Looking inside the structure at the collapsed floor due to scour of the sand beneath the slab-on-grade floor

Looking inside the structure at the collapsed floor due to scour of the sand beneath the slab-on-grade floor.

STRUCTURE 81. This residential structure was located about two blocks from the beach. The first-floor living area was well elevated. The lower (at grade) area was fully enclosed with non-breakaway walls and was used as a garage and utility room. Between this structure and the beach was a multistory residential structure. Structure 81 endured the storm forces well.

Lesson. This structure was recently constructed. It had adequate elevation and was constructed to state-of-the-art building codes. Because of its location two blocks from the beach and behind a large multistory building that may have provided some protection from hydrodynamic force, the degree of hazard was lower than had it been located directly on the beach. A note of caution with this structure is the enclosed lower area. This type of enclosed construction, unless the walls are able to break away during a hurricane event, subjects the structure to hydrodynamic force and the potential for foundation scour due to the obstruction to waterflow caused by the enclosed walls at ground level.

Looking at the structure. The beach is in the far background behind the multistory building.

STRUCTURE 82. This multistory residential complex was elevated on reinforced concrete columns that sustained minimal damage. It was located directly facing the beach. The structure's first floor was elevated several feet above beach level and was used for automobile parking. The first habitable floor was two floors above the ocean level. The structure was protected from scour by a concrete wall.

Lesson. This structure was successful for two basic reasons. It had both proper elevation and proper scour/erosion protection. The first damageable floor was well above the flood level since it was two floors above the ocean level. The first floor was occupied by automobiles which can easily be moved to a nonhazard area with proper warning time. Scour did not pose a problem because of the wall and the proper column embedment depth.

Looking from the beach at the structure.

STRUCTURE 83. This structure was a motel complex consisting of two buildings with two habitable stories each. A concrete swimming pool was located between the two buildings. The structures were elevated above the beach but not enough to prevent first-floor flooding. The structure directly faced the beach. Support was provided by 8-inch wooden piles approximately 9 feet on center. These piles were braced by wooden "x" bracing. The floor of each building was a concrete slab placed on sandfill. From visual inspection, it could not be determined if rebar was present in the concrete slab. Severe scour occurred around and beneath the buildings to the extent that the buildings, which prior to the event appeared to be “at grade,” were, after the event, elevated about 5 feet above the grade after scour. The concrete swimming pool, which was supported on sandfill, had dropped several feet from its pre-event elevation because of scour of the sandfill

Lesson. Severe scour occurred around and under these structures during the event. The wood piles appeared to be improperly sized, since some were visibly leaning under the weight of the buildings without sandfill support. The “x” bracing on the piles may have saved the building from collapsing. This shows the need not only for proper embedment depth of posts or piles but also for proper size of posts or piles for needed strength. In this case, where sandfill appears to have been factored in as a part of the building support/stability system, a protection wall around the building that could have withstood the scour hazard and hydrodynamic force should have been built. The most proper design, however, would have been to elevate the buildings on larger diameter piles that were completely independent of sandfill for added support to the buildings.

Looking at the structure and beach. Prior to the event, the “grade” elevation at the far right extended toward the beach and under the structure.

Looking from the beach at the structure. Note the collapsed swimming pool between the structures.

STRUCTURE 84. This structure number represents structures that directly faced the beach but were set back a considerable distance, were elevated relative to sea level, and have been protected by a sand dune with natural vegetation. In this case, the dune appeared to be natural but could just as well have been manmade. The combination of higher elevation, greater distance from the beach, and/or existence of a natural dune provided good protection to these structures.

Lesson. "Conventional" construction techniques in the structure itself are often very adequate to mitigate hazards from floods, erosion, and hydrodynamic force if other nonstructure-related techniques are employed. In this case, constructing structures on higher ground is a large step toward hazard mitigation in the form of reduced flood damages. A large setback allows room for either a natural or a manmade dune to be located between the ocean and the structure. This can diminish or eliminate hydrodynamic force on the structure and the potential for scour at the structure.

Looking along the beach at the structure and the dune. Note the structure elevation and the dune protection.

Looking along the beach at the structures and the dune. Note these structures are not elevated as high as those in the above photograph but the dune has much more vegetation.

PENSACOLA, FLORIDA

STRUCTURE 85. This structure, which was constructed on a barrier island, faced the beach. The structure was a three-story wood-frame building with the first floor elevated by wood-frame construction on shallow footings. Very high flood velocities were experienced in this area as floodwater flowed across the barrier island. Floodwater depths of about 4.5 feet were directly impinging on the structure. Localized scour occurred, which undermined the shallow foundation and caused one-fourth of the structure to collapse.

Lesson. Two basic factors caused the collapse of one-fourth of the structure. First, the construction on the barrier island placed the structure in jeopardy due to high-velocity floodwater, creating both a hydrodynamic force hazard and a scour hazard. Construction in areas such as this should be avoided. Second, the structure foundation that was situated in sand should have been much deeper to resist the forces of erosion caused by the high velocities and compounded by the obstructive nature of the structure.

Looking at the structure from the beach.

STRUCTURE 86. This structure, which directly fronted the beach, was a one-story, single-family wood-frame home elevated approximately 8 feet on wooden piles. It had an enclosed lower area for storage of utility items. Embedment of the wooden piles was adequate to withstand scour from this event. This structure survived well, as did other structures of this type similarly elevated.

Lesson. This structure survived well in this event. However, the enclosed lower area could have created a problem due to the obstructive effect of the floodwater creating hydrodynamic force against the enclosed area and higher localized velocities as floodwater flowed around the enclosed area. This effect could cause excessive localized scour to depths not anticipated in sand, undermining pile supports and causing failure. It is best in warm climates, such as occurs in Florida, to have lower level storage areas enclosed with "jail-type" spaced bar construction so floodwater can flow through, eliminating hydrodynamic force and scour potential.

Looking along the beach at the structure.

STRUCTURE 87. This was a two-story, single-family residential structure elevated on 12-inch-diameter wooden piles. The piles were of such length that they extended from embedment depth up to the roofline so the entire structure was tied together by means of the wooden piles. Hurricane-type steel fasteners were in place. The first floor was elevated 8 feet above grade, with the lower area entirely unobstructed. The structure was under construction at the time of the event.

Lesson. This structure was designed to accommodate hurricane hazards from wind, flooding, and scour. One possible weakness was observed at the intersection of the main floor with the wooden piles. The wooden piles were notched to accommodate a resting place for the main floor sills to the extent that the 12-inch-diameter wooden piles were reduced in diameter to approximately 6 inches. This weakens the effectiveness of the piles' ability to bond the entire structure together in terms of the ability to withstand hurricane force winds.

Looking at the structure with the beach in the background.

STRUCTURE 88. This structure was a single-family, wood-frame home elevated on columns made of concrete block with a one-half-inch rebar grouted into each hole of the concrete block. This made a reinforced concrete block column for use in elevating the structure about 8 feet above grade. The structure was about 300 feet from the beach on the landward side of a beachfront street. The structure survived the event well, except for the reinforced concrete block columns, which sustained severe cracking apparently from the torsion effect of the hurricane force wind against the structure. No "x" bracing was used between the columns. The columns appeared to be close to failure.

Lesson. Reinforced concrete block columns of this design are not appropriate in coastal areas where high wind forces occur against a structure. The concrete block columns should have contained more rebar in order to provide rigid strength against the hurricane force winds. The best alternative is to use piles that have the ability to resist this type of force without becoming damaged.

Looking at the structure.

Looking at the column support that was nearing failure.

STRUCTURE 89. This structure was a new, one-story, single-family home elevated on wood piles. It directly fronted the beach. The structure employed proper elevation, wood piles for support, proper pile embedment depth, minimal floodwater obstruction, and proper wind proofing. The structure received minimal damage during the event. It was the only structure in the reach that survived.

Lesson. This structure survived the event well because it incorporated proper design and construction to withstand hurricane force winds, flooding, and hydrodynamic force associated with such a storm.

Looking at the structure. Note the beach at the left. Note also the absence of adjacent structures, which had been destroyed and removed.

EASTERN CALIFORNIA AND WESTERN NEVADA

Severe flooding occurred in January 1997 as a result of heavy snowfall followed by heavy rainfall in the Sierra Nevada Mountains of eastern California and western Nevada and the adjacent "foothills" of eastern California. The occurrence of heavy rainfall on the already present snowpack created tremendous runoff, resulting in flooding along the Sacramento and San Joaquin Rivers and their mountain tributaries in California and along rivers such as the Truckee in western Nevada.

SACRAMENTO, CALIFORNIA

STRUCTURE 90. This structure was a one-story single-family residence with a slab-on-grade foundation. The structure was located about 70 feet from the Sacramento River between the river and a levee. It was oriented with its largest dimension parallel to the river. The Sacramento River at this location was above flood stage for about 2 weeks. There was ample warning time prior to the flooding. The structure was protected by a floodwall made of 100 percent grouted concrete block. Horizontal and vertical steel reinforcement was in the wall. The original wall was built prior to 1986. Subsequent to 1986, the wall was extended upward 26 inches with $^3/_8$ inch rebar located every 32 inches to tie the new wall to the old wall. The maximum height of the wall above ground was 64 inches. The minimum distance of the wall to the structure was 3 feet. The wall surrounds the structure on three sides. The wall tied into the levee, a "mainline" levee protecting the City of Sacramento, which provided protection on the fourth side. The floodwall had two openings in it on that portion paralleling the river. The openings were 3 feet and 8 feet wide. The 3-foot-wide opening was closed with a single piece of $^5/_8$ inch plywood attached by screws to the concrete block floodwall. Caulking was applied to the joints, and sandbags were piled at the bottom on both the protected and the river sides. The closure was 56 inches high. Plastic sheeting was placed over the closure on the river side. The 8-foot-wide closure was constructed similarly, with the exception that it was made of double 1-inch-thick plywood with bracing on the protected side consisting of 2- inch by 4-inch lumber placed horizontally and vertically at the center of the closure with a diagonal 4-inch by 4-inch brace from the center of the wall to the concrete floor. A sump pump was present near the 8-foot-wide closure. The 1997 flood was up about 40 inches on the floodwall. The owner/resident waged a flood fight during the flood.

Lesson. This flood proofing system failed, inundating the structure up to the level of the flood. Failure occurred for basically two reasons. Excessive water seepage occurred at the 8-foot-wide closure due to inadequate sealing on the bottom and sides of the closure. To prevent this seepage, this closure, because of its width, should have been constructed of more rigid material such as aluminum with manufactured sealing membranes that would have increased sealing capability with increased hydrostatic force. This large closure was very critical and needed a "state-of-the-art" closure. The excessive seepage exceeded the capacity of the sump pump, causing water to accumulate on the concrete floor. This sump pump was powered by an electrical cord lying on the floor. The seepage water covered the cord, causing a "short" to occur and stopping the sump pump. Before power could be restored, seepage water continued to accumulate and flowed about 40 feet along the wall to a location where excavation had occurred for utility work sometime prior to the flood. The excavated area had not been properly compacted. The wetting of the poorly compacted excavated area and the hydrostatic force of water 40 inches high on the wall created "piping" that caused massive failure under the wall. The owner/resident was fighting the flood at the time of failure. In this case, he was able to escape because the fourth side of the protection was the "mainline" levee that provided a nearby safe evacuation route. If the floodwall had surrounded the structure and floodwater had surrounded the floodwall, no safe excavation route would have been available. This is a large concern when employing flood proofing measures such as levees, walls, or dry flood proofing where sump pumps are needed to evacuate seepage water and rainfall and owners tend to remain onsite to flood fight. For safety reasons, flood proofed structures should always be evacuated prior to being surrounded by floodwater. To do this, a fail-safe sump pump system needs to be employed--one that has redundancy so if one system fails another will come "online" automatically with or without electrical power. Another alternative is to manually switch the power source for the sump pump from an electric powerline source to either battery or generator, depending on the anticipated length of flood.

Looking along a portion of the floodwall. The failure under the wall occurred in the immediate foreground. Note the largest closure at the right of the structure. Also note the Sacramento River in the background.

Looking at the largest closure structure and sump pump. Note the electrical cords on the concrete floor.

STRUCTURE 91. This was a multistory floor, single-family, slab-on-grade structure located about 30 feet from the Sacramento River between the river and a "mainline" levee that was located about 50 feet from the structure. The structure was protected by an earthen levee located between the river and the structure and tying into the mainline levee. The levee had been in place about 15 years. Levee compaction was questionable.

Lesson. The flood proofing measure failed due to overtopping of the levee. Sandbags had been placed on top of the levee but were not able to prevent overtopping and erosion of the protected side of the levee as water flowed over the top. More levee erosion would have occurred, leading to levee breaching, if the protected area had not been so small, allowing for rapid equalization of the water surfaces on both the protected and unprotected sides of the levee. Obviously, this levee was not high enough since it was overtopped in 1997 and also in 1986. The real lesson to be learned at this structure and also at Structure 90 is the choice of flood proofing measure. In these cases, the site location on a narrow strip of land between a major river and a "mainline" levee should be strongly considered when selecting a flood proofing measure. The ultimate flood proofing measure is relocation.

Elevation or wet flood proofing, with the protected level no lower than 1 foot above the top of the mainline levee, would be the next choice. Barriers such as levees, walls, or dry flood proofing are not a good choice in locations such as the locations of Structures 90 and 91 because of the large height required for these measures to achieve protection to at least 1 foot above the top of the adjacent "mainline" levee.

Looking along the overtopped levee. Note the Sacramento River at the left and the low elevation of the developed first floor of the structure relative to the river elevation.

RENO, NEVADA

<u>STRUCTURE 92</u>. This structure was a multistory public building located within about 100 feet of the Truckee River. The building was constructed in 1996. The building walls were constructed of reinforced concrete. Ample warning time prior to flooding was present. The lower level was flood proofed by wet and dry flood proofing. The wet flood proofed area was used for building access and vehicle parking. The remainder of the lower level was dry flood proofed by using waterproofed reinforced concrete with a state-of-the-art closure panel consisting of metal construction with a pneumatic seal on all sides except the top, which left a gap in all closures of about 8 inches.

Lesson. The wet flood proofing measure functioned properly, with apparently little damage in this part of the lower level. The dry flood proofing measure however, failed. This measure was designed for 1 foot above the 100-year flood. The flood event of January 1997 exceeded that level. Floodwater overtopped the closure panel completely, inundating the protected area. Obviously, the closure panels and the reinforced concrete walls should have been designed for a higher level of flooding that would have completely closed all openings. The state-of-the-art metal panels with a pneumatic seal functioned as designed without damage. They were simply not high enough. In addition, it was reported that floodwater was already about 1 foot deep in the protected area before floodwater overtopped the closure panels, indicating water was leaking through the waterproofed reinforced concrete. The most reliable waterproofing method for reinforced concrete is to "sandwich" a nonpermeable membrane between the layers of concrete. No damage was apparent to the actual reinforced concrete wall due to hydrostatic force.

Looking at the structure. The Truckee River is immediately to the right.
The flood proofed floor is at the automobile level.

Looking at a doorway into the "protected" area. Note the state-of-the-art pneumatic seal closure at the left in its storage position. Also note the gap between the top of the closure and the top of the doorway.

STRUCTURE 93. This structure was a single-story, slab-on-grade building located about 50 feet from the Truckee River. It was built in 1989 just downstream from a city bridge over the river. It was flood proofed by elevation on fill to a level 2 feet above the 100-year flood. A flood fight was waged with sandbags and plastic sheeting at openings on the upstream side of the building. The downstream side of the building was higher than the floodwater.

Lesson. This structure and its contents had minimal damage due to the flood proofing measure of elevation on fill and the flood fight. The lesson for this structure consists of four parts. First, the flood proofing measure enabled a flood fight to be successful. Second, a decision had to be made based on upstream flood information that a successful flood fight was possible while still keeping safety in mind for the flood fight personnel (since a basic parameter of flood proofing is to evacuate). Third, the impact of debris in the upstream bridge needed to be considered. This was evidently overlooked when the flood proofing elevation was selected. In the flood event, the upstream side of the bridge filled with debris to the extent that floodwater was forced out of the channel and onto the street just upstream from the structure at an elevation higher than the computed water surface elevation for a flood of this magnitude without the obstructive effect of the bridge. The fourth part of the lesson concerns the value of the contents in the structure. The contents consisted of $25 million worth of nonreplaceable antique automobiles. Contents that are nonreplaceable should always be located in a flood-free location.

Looking from the upstream street downstream at the structure.
The doors in the background are one of the flood fight locations.

<u>STRUCTURES 94, 95</u>. These structures were both slab-on-grade commercial buildings located several hundred feet from the Truckee River. The area was subject to only shallow flooding. These structures are presented to illustrate a type of earthen embankment that can be very effective in flood proofing against relatively shallow, short- duration floods. Structure 94 had been landscaped well to blend into the surroundings and be aesthetically pleasing. This embankment was a permanent flood proofing measure. The embankment protecting Structure 95 had just been constructed. It could be removed after the flood event or remain as a permanent measure. Sandbag closures across vehicle access routes were necessary.

<u>Lesson</u>. These flood proofing measures were successful. Earthen embankments, especially in shallow-depth flood areas of short duration, can be quite effective if placed on a permanent or temporary basis. Obviously, all parts of an earthen embankment flood proofing measure such as interior drainage, closures, and so forth must be present and functional.

Looking along the earthen embankment with Structure 94 on the right. Note the raised handrail as the pedestrian entry to the building passes over the embankment.

Looking at the recently constructed earthen embankment protecting Structure 95. Note the plastic sheeting at the far right that was placed over the embankment's unprotected side and held in place with sandbags to provide impermeability to the embankment.

LOWER PLATTE RIVER, NEBRASKA

Serious ice-jam flooding occurred along the Lower Platte River in Eastern Nebraska in February 1997. The ice-jam flooding resulted from late winter snowmelt runoff entering the river prior to breakup of the winter accumulation of ice. Due to the presence of ice in the river, ice jams occurred, causing serious flooding in localized areas. The flooding in some areas also contained large amounts of thick river ice chunks, which added to the associated hazard.

STRUCTURE 96. This structure represented several two-story, dormitory-type structures elevated on reinforced concrete posts that were tied to footings thus forming piers.

The posts were 16 inches in diameter and were located 16 feet apart. They were composed of concrete reinforced with six No.6 vertical rebars and eight No. 7 vertical rebars. The posts rested on reinforced concrete footings varying in size from 8 feet by 8 feet by 16 inches thick to $5^1/_2$ feet by $5^1/_2$ feet by 14 inches thick. The footings were tied to each post with rebar. The footings were 4 feet in the ground. The lowest elevation of the elevated building was 1 foot above the 100-year flood. A utility corridor existed, measuring 5 feet by 5 feet and extending from the ground to the elevated building. This corridor was waterproofed, was built of reinforced concrete to resist hydrostatic force and had a watertight closure door used for access.

During the 1997 flood event, about 3 feet of floodwater inundated the area beneath the elevated buildings. Massive ice blocks also floated beneath the elevated buildings, directly impinging upon the posts. Floodflow velocity was moderate. No damage occurred due to either floodwater or the impact of the ice blocks.

Lesson. This flood proofing system performed very well in this flood event. The buildings were elevated enough to be above the flood elevation and the posts were strong enough to withstand the impact of floating ice blocks without damage. Erosion was not a factor for the event.

Looking at one of the elevated buildings.

Looking at the massive ice blocks that passed through the area.

RED RIVER OF THE NORTH, MINNESOTA AND NORTH DAKOTA

Historic flooding occurred along the Red River of the North in Eastern North Dakota and Western Minnesota in April 1997. The flooding resulted from the melting of an extremely heavy snowpack that accumulated during the winter of 1996/1997.

EAST GRAND FORKS, MINNESOTA

STRUCTURE 97. This structure was a one-story, single-family residential building with a basement. It had an attached double car garage on its east side. It was constructed about 1990. The structure was wood-frame construction resting on foundation walls of reinforced poured concrete. The soil surrounding the structure was a mixture of silt and clay. The structure was about 350 yards from the Red River and was protected by a "mainline" levee located close to the river channel bank. The structure was dry flood proofed. The basement floor and walls were constructed of 8-inch-thick concrete with $^{1}/_{2}$-inch rebar located horizontally and vertically every 6 inches. A nonpermeable neoprene membrane was located in the middle of the 8-inch-thick walls and floor. The structure did not have a sump pump. Velocity was not a factor. The first floor was about 3 feet above ground and about 2 feet above the 100-year flood.

Lesson. This structure was dry flood proofed at a far greater expense than conventional construction of adjacent foundation walls and floors in the neighborhood that were not flood proofed. Only one mistake was made, but it proved to be very costly. The effects of hydrostatic force were considered structurally in the strength of the walls and floor of the basement but not in the ability of the structure to resist uplift force (buoyancy). The designer of this flood proofing system specified that in order for the structure to resist buoyancy, the structure owner needed to fill the basement with a minimum of 42 inches of water. The structure owner chose not to do this. Upon failure of the mainline levee, floodwater surrounded the dry flood proofed portion of the structure and entered the garage, which had a floor at grade. The flood peak was 20 inches deep on the garage floor but was still below the design level of the dry flood proofing measure. However, within 12 hours of floodwater surrounding the structure, the hydrostatic force lifted the west edge of the structure as much as 4½ feet. The eastern edge of the dry flood proofed part of the structure was held in place by the attached garage. Damage to the structure resulted from the unequal lifting of the structure (structural damage) and rupture of the utility lines that entered the basement (floodwater entry). Signs of an electrical fire in the outside panel box were evident, probably as the electrically charged underground lines were pulled from the panel box as the structure lifted. The irony of this example is that the structure that was dry proofed was considered severely damaged while adjacent structures that were not flood proofed only incurred damage due to water in basements but were structurally sound and could be reoccupied. This example points out the difficulty of dry flood proofing a structure with a basement because of the effects of hydrostatic force. In this case, at least five items should have been done further to help offset the effects of hydrostatic force while not purposely placing water in the basement. One, the soil around the basement wall should have been properly compacted to make the soil as impermeable as possible. Two, a drain field should have been installed around and beneath the basement floor leading to a sump pump to reduce hydrostatic force buildup by evacuating water. Three, the design should have incorporated measures to ensure that the floodwater never touched the basement wall. Four, as part of the floor, a structural anti-buoyancy device consisting of basically a floor slab extending beyond the walls but tied to the floor with rebar so the weight of the soil would act to offset the hydrostatic force against the basement floor should have been installed. Five, "blowout plugs" should have been installed in the floor. These plugs are designed to withstand hydrostatic force but will "blow out" prior to hydrostatic force making the structure buoyant. Soil permeability is obviously very critical. In this example, a silt clay soil should have been able to resist saturation longer than 12 hours. Improper backfill material type and compaction adjacent to the structure may have been major components leading to such rapid saturation of this soil type. In this specific case, since the owner knew that items two through five were not part of the design, the basement should have been purposely flooded with at least 42 inches of water prior to evacuating the structure. This was done to a similarly flood proofed structure in the area and only minor water damage occurred to the unfinished basement.

Looking at the structure. Note the garage on the right that held that part of the structure down and the exposed basement wall on the left indicating the amount of lifting that occurred on the west side.

OAKPORT, MINNESOTA

<u>STRUCTURE 98.</u> This was a one-story, single-family residential building with full basement. The floor was about 1 foot above grade. This flood event was about 2 feet below the floor and about 1 foot below grade at the structure, making the floodwater at the peak a few feet from the structure. The soil was a very impermeable clay. The basement walls and floor were 8-inch-thick reinforced concrete with a drain network around the basement wall perimeter and under the basement floor leading to a sump pump. The walls contained No.4 horizontal rebars and No.4 vertical rebars spaced a maximum of 6 feet apart. Rebar overlapping was a minimum of 12 inches. The No. 4 rebars were placed 18 inches on center to tie the wall to the footing. Window wells constructed to the same specifications as the basement walls were present. A waterproofed membrane was not located in the basement walls or floor. The flood duration was about 7 days. The structure was about 1,000 feet from the Red River of the North.

<u>Lesson</u>. This flood proofing measure functioned well. The three reasons why this flood proofing measure was successful versus that for Structure 97 (which was unsuccessful) are as follows. One, the soil at Structure 98 was more impermeable. This was the main factor. Two, floodwater remained probably 10 to 15 feet from the structure so water could not easily penetrate between the soil and the structure. Three, a good drain network leading to a sump pump was in place. This allowed evacuation of the water that was able to penetrate the soil. It should be noted that concrete blocks should not be used in this dry flood proofing system because they do not provide the strength that a poured concrete wall provides.